LCRD Optical Ground Station 1

W. Thomas Roberts
Jet Propulsion Laboratory
The California Institute of Technology
Pasadena, CA
tom.roberts@jpl.nasa.gov

Sabino Piazzolla
Jet Propulsion Laboratory
The California Institute of Technology
Pasadena, CA
sabino.piazzolla@jpl.nasa.gov

***Abstract*—NASA's Laser Communications Relay Demonstration (LCRD) will demonstrate and study bi-directional space-to-ground optical links. Optical Ground Station 1 (OGS-1) for LCRD will be developed at the Optical Communications Telescope Laboratory (OCTL), a 1-meter telescope in the San Gabriel Mountains northeast of the Jet Propulsion Laboratory. This paper will present an updated overview of OGS-1, its systems and capabilities, and its preparations for integrating and verifying readiness of the completed system. It will conclude with predicted performance of the OGS-1 system.**

Keywords*—*LCRD, Laser communications, OCTL, optical ground station, networking, adaptive optics, atmospheric monitoring

I. Introduction

NASA's Laser Communications Relay Demonstration (LCRD) project is designed to support space-to-ground and ground-to-ground optical communications relay links through an orbiting platform in geostationary orbit [1][2]. NASA's Goddard Space Flight Center is developing the LCRD orbiting platform with two independently-pointed optical modules capable of pointing at different remote platforms, whether orbiting or ground-based, to maintain a continuous 'bent-pipe' bi-directional link. These optical modules are similar to the Lunar Laser Communications Demonstration (LLCD) optical module developed by the Massachusetts Institute of Technology's Lincoln Laboratory, which supported high-bandwidth optical communication links from lunar orbit directly back to ground stations on Earth [3][4].

Optical Ground Station 1 (OGS-1) is in development by the California Institute of Technology's Jet Propulsion Laboratory (JPL), to act as the primary ground station for the LCRD operational demonstration. The principal component of this ground station is the Optical Communications Telescope Laboratory (OCTL) at the Table Mountain Facility (TMF) near Wrightwood, CA. The design of OGS-1 draws heavily from the design of the Lunar Laser OCTL Terminal (LLOT) also developed at OCTL, which successfully supported lunar-earth optical links during the LLCD project [5].

JPL is also contributing to the development of a number of key technologies for LCRD that will facilitate improved performance and demonstrate the networking capabilities expected of a multi-functional operational relay system.

II. Optical Ground Station 1 Sub-Systems

OGS-1 is comprised of eight independent sub-systems as shown in the system block diagram (Fig. 1). An overview of each subsystem is provided below. More detail on the various subsystems can be found in a previous paper [6].

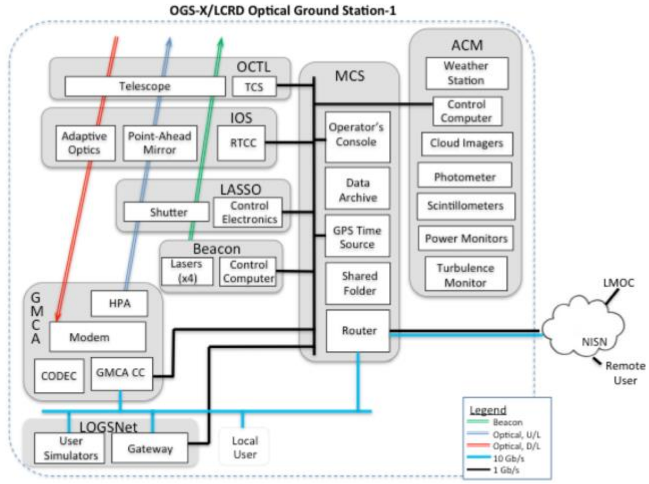

Fig. 1. Block Diagram of OGS-1 showing major subsystems.

A. *The OCTL Telescope*

The OCTL telescope is a 1-meter diameter classical Cassegrain telescope with a fast F/1.5 primary mirror followed by a hyperboloidal secondary mirror with a focal length of -856 mm to generate an F/76 beam to the focal plane in the coude room below the telescope [7]. The tertiary flat is centered on the telescope's elevation axis in front of the primary mirror. It is followed by four additional identical fold flats which direct the light down the azimuth axis of the coude path to the final fold flat. This final flat mirror (M7) is mounted on a precision rotation stage for directing the light to any of four distinct experiment tables, allowing concurrent setup and use of up to four different experiments.

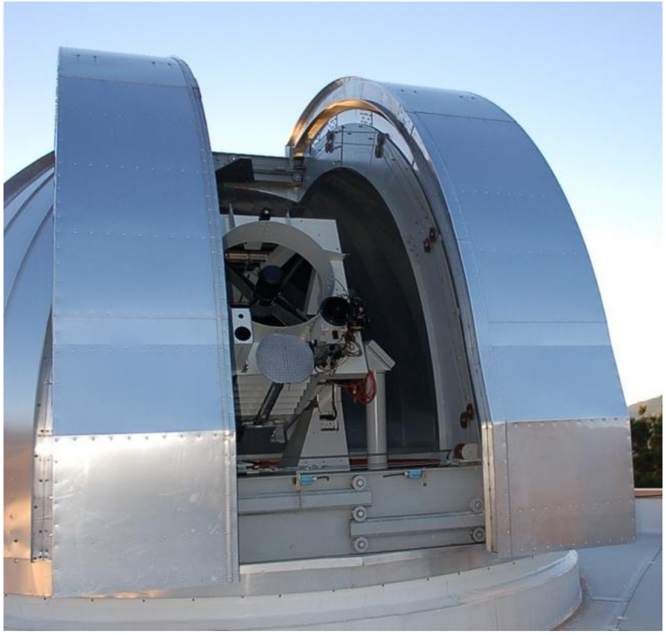

Fig. 2. The OCTL 1-meter telescope

While the light sources of interest overhead may constantly move, the telescope can, in a reliable and repeatable fashion, direct the light from those sources to a stationary, stable experiment in a relatively clean, thermally controlled environment. The penalty paid for this convenience is that, though the focal plane position remains fixed, the image and telescope pupil rotate in the coude room as a function of telescope elevation and azimuth, and as a function of M7 orientation.

B. *Integrated Optical System (IOS)*

The IOS acts as the optical interface transferring received signal to the ground receiver system known as the Ground Modem [8]. It also prepares the beacon and communication beams for transmission through the telescope onto the sky. The receive system makes use of an advanced Adaptive Optical (AO) System to focus the atmospherically-aberrated downlink beam from the spacecraft into the single-mode fiber input to the modem. This AO system is designed to couple the received signal to the modem input fiber under relatively severe conditions of 20 degrees elevation angle at a site with r_0 (Fried's parameter) of 3.5 cm. The level of turbulence to be corrected required both a significant amount of stroke, as well as the need to apply fine corrections at relatively high spatial frequency. This complicated the system by forcing the adoption of a 'woofer-tweeter" approach in which a deformable mirror with high stroke (*i.e.*, the woofer) is employed to take out the high-amplitude aberrations, while a 'tweeter' deformable mirror with a higher density of actuators is used at an optical conjugate to resolve the high spatial frequency aberrations.

The AO system in the IOS splits off 20-30% of the light in the AO system to a Shack-Hartmann wavefront sensor for mapping the structure of the wavefront. Just after the split to the Shack-Hartmann sensor, an additional 1% of the received light is diverted to a scoring camera for evaluating the performance of the AO system, and for comparison with the power received by the modem.

The transmit side of the IOS independently controls the four beacon beams and the single communications beam, aligning them and directing them out the telescope to the LCRD spacecraft location. The beacon beams are modified to produce a 280 μrad beacon spot on the sky. The single communication beam is converted into a much narrower 20 μrad beam to be directed at the spacecraft. The narrow profile of this beam dictates that it must be independently steered to account for the 18 μrad point-ahead angle. The five beams each reflect from different portions of the telescope's primary mirror, so that atmospheric disruption of the pointing of any one of the beams is independent of the performance of the other beams.

The transmit and receive sides of the IOS are combined by a high efficiency dichroic beam splitter placed near the telescope focus. This element makes use of the spectral separation among the downlink receive beam and the uplink transmit beams to efficiently direct the uplink beams out the telescope. Meanwhile, the downlink beam from the spacecraft passes through the dichroic element with over 95% efficiency on its way to the AO system.

An atmospheric turbulence simulator capable of simulating the range of turbulence conditions expected at the OGS-1 site is included in the IOS system. We plan to use this simulator extensively to test and refine the performance of the AO system throughout development and integration of the IOS system.

C. *The Atmospheric Channel Monitoring Sub-System*

A primary goal of the LCRD experiment is to understand the potential of, and likewise the constraints on, the performance of ground-to-space communications. Propagation of high-rate optical signals through the atmospheric optical channel is expected to be one of the limiting factors of signal reliability and availability. The Atmospheric Channel Monitoring System (ACM) is our primary tool for gathering data to investigate the correlation between LCRD communications performance and atmospheric conditions at the ground station site. The ACM incorporates:

(1) A weather station for monitoring temperature, wind speed, wind direction, local humidity and precipitation,

(2) A Wide-Field cloud monitoring system to evaluate general cloud conditions, sky radiance, and cloud optical depth,

(3) A Narrow-Field cloud monitoring system to evaluated immediate conditions of sky radiance and optical depth along the line of site to the spacecraft,

(4) A Solar Scintillometer for measuring the path-integrated atmospheric scintillation along the path to the Sun, and

(5) A Boundary Layer Scintillometer for measuring the scintillation contribution of the local boundary layer.

The ACM also makes use of a Radiance/Irradiance Sensor (Fig. 3), attached to the OCTL acquisition telescope and co-aligned with the main telescope. This sensor measures the sky

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

radiance in visible and 1550 nm bands, as well as the irradiance of the downlink laser beam from the spacecraft. This gives a more direct measure of received power, necessary for characterizing the performance of the receive optics and AO system.

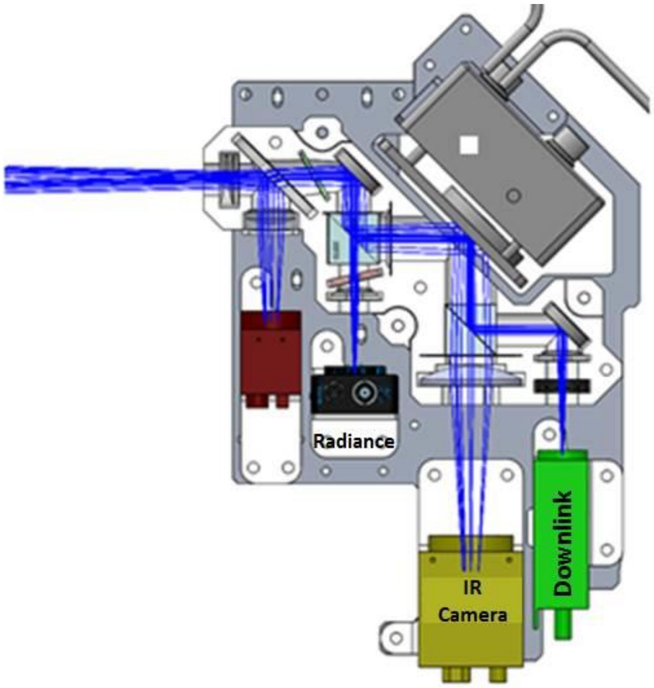

Fig. 3. Schematic of the Radiance/Irradiance Sensor system attached to the OCTL acquisition telescope.

D. The Ground Modem, Codec and Amplifier Sub-System

The Ground Modem, Codec and Amplifier (GMCA) is built by GSFC for delivery to OGS-1 in mid-2018. The GMCA control computer oversees, monitors, and coordinates its functions. The modem portion of the GMCA modulates and demodulates the signal as either a Differential Phase Shift Keyed (DPSK) or a Pulse Position Modulated (PPM) signal. DPSK signals are more capable of high-rate communications with existing laser and modulation technology, as long as the signal strength is high. However, for deep space applications, PPM signals offer high photon efficiency; pulse position modulation is an effective and proven method of trading bandwidth for energy efficiency over range. The LCRD plan incorporates demonstrations and investigations of both modulation schemes.

The Coder/Decoder (Codec) hardware implements a DVB-S2 concatenated code consisting of a rate 1/2 Low-Density Parity-Check (LDPC) inner code and a Bose, Chaudhuri, Hocquenghem (BCH) error correcting outer code [6].

The final portion of the GMCA consists of an OFS High Power laser Amplifier (HPA), capable of delivering the 10 W average power modulated communication signal. This laser has a free-space single-mode output which must be collimated by the optics of the IOS transmit system and shaped appropriately to go through the telescope.

E. The Beacon Laser Sub-System

The beacon laser subsystem consists of four DFB seed lasers in the 1550 nm band, amplified to 2.5W each by two stage fiber amplifiers. The lasers are independently modulated with a continuous low-rate modulation to aid the spacecraft in locking onto their signal. The lasers are thermally tuned to within +/- 10 GHz. The four beams are propagated through different portions of the telescope pupil to reduce the beacon beam fading. They are overlapping in the telescope focal plane, which assures that they will overlap in the far field on the sky.

The beacon subsystem monitors the health and status of each laser, and records their measured power and precise wavelengths. This data is reported once each second to the monitor and control system which maintains the comprehensive database of subsystem performance for correlation with link performance.

F. The Laser Safety System at OCTL (LASSO)

The OGS-1 LASSO system has been developed to support the safe operation of OGS-1 for LCRD. The system is designed as a fail-safe system, in which a continuous signal from the control computer must be present to maintain a laser shutter in an open position. A watchdog timer assures that the signals coming from the computer are valid and timely. When closed, the gold-coated shutter blades reflect the laser power into an air-cooled laser beam dump.

The beacon and communications lasers are considered eye-safe outside the telescope dome, so coordination with the USAF Laser Clearing House is the only external cause for shuttering the lasers. To extend the usefulness of the system, we have developed the software so that additional sensors (i.e. radar, IR sensors, ADSB, etc.) can be used to interrupt the 'open' signal, triggering the shutter.

G. The Monitor and Control Sub-System

The Monitor and Control System (MCS) acts as the central processing system for collecting information from and sending commands to the various other subsystems. It is designed around a client-server architecture, communicating with the other subsystems over a 1 Gbps MCS LAN.

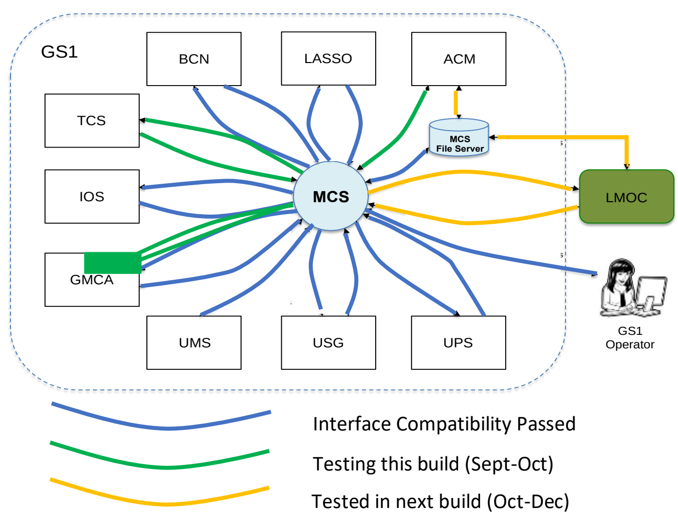

Fig. 4. OGS-1 Monitor and Control System status

The MCS is also responsible for supporting schedule-driven operations, in which operational schedules disseminated by the LCRD Mission Operations Center (LMOC) are interpreted and executed by the MCS. MCS parses the schedule, configures the various OGS-1 subsystems for required performance, and executes the schedule in a synchronized fashion once the time server signal reaches the appointed execution time.

H. The LOGSNet Networking Services Sub-System

The LOGSNet networking services subsystem, developed by the team developing OGS-1, is a major feature of the LCRD project. It establishes the means by which multiple services of differing types, resource requirements and traffic profiles can be seamlessly executed, thereby constituting a real operational system demonstration. The LOGSNet system provides a User Services Gateway (USG) for controlling the information flow through the LCRD link, a User MOC (Mission Operations Center) Simulator (UMS) for simulating a ground–based user connection, a User Platform Simulator (UPS) for simulating a space link to the LCRD spacecraft, and a Channel Simulator for perturbing signals to simulate the effects of loss, background, scintillation and fade in the optical channel.

The LOGSNet system connects with the MCS over the 1GBPS Ethernet MCS LAN so that it can be independently configured and controlled by the MCS, and relate system status and performance metrics back to the MCS for archiving and transfer. However, user data, whether simulated by the UMS or UPS or provided by a real user, is transferred among components of the LOGSNet system and the GMCA control computer over a 10GBPS User Access Network (UAN) LAN.

The LOGSNet system is designed to be capable of supporting up to 12 simultaneous virtual channels, at an aggregate rate of up to 1.24 GBPS when operating under DPSK (321 MBPS under PPM). The service types supported include Symbolstream, Bitstream, Internet Protocol (IP) Service, and the CCSDS Advanced Orbiting Systems (AOS) service type. To support ground links, the potential for Space Link Extension (SLE) is supported through user-supplied networking equipment.

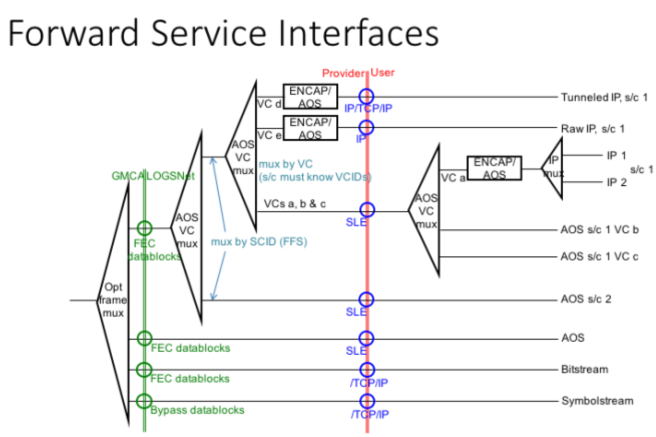

Fig. 5. LOGSNet supported service types, framing architecture and interfaces for forward service. A similar diagram describes the return service architecture.

The LOGSNet system is configured by the MCS for operation according to the schedule distributed by the LMOC. Along with the schedule, a traffic profile is distributed by the LMOC, which specifies the types of services to be established, as well as the data rates, start times and stop times of each particular service. The LOGSNet user simulators use this information to start up services with the USG, flow the relevant type of data across the UAN at the specified rate, and

Additional units of the MCS and LOGSNet systems are being developed for supporting additional LCRD ground stations.

III. OGS-1 Integration and Testing

We plan to take advantage of the staggered delivery of the various OGS-1 subsystems to support a phased integration of OGS-1 during the latter part of 2017 and early 2018. Integration at a remote telescope is a difficult, inefficient, costly undertaking. To limit the adverse effects on personnel, we will conduct the integration of subsystems into two parallel lines, merging them during the latter half of integration as the separate lines mature. A natural division of these two lines is found in the separation between optical systems, and electrical/networking systems. The optical systems (telescope, Beacons, IOS and LASSO) must be aligned together optically, and thus must be integrated at the telescope. This allows them to be co-aligned to within tight tolerances at the facility where they are to be used. During this early phase of integration, the transmit system is also to be assembled and aligned to the telescope.

Integration of the MCS and LOGSNet will take place in the less demanding, more controlled environment of the JPL laboratory until the delivery of the GMCA in mid-2018. This affords these systems the ability to do intensive integration of the MCS and LOGNet system, and concentrate on supporting the MCS scheduling and operational interface with the LMOC. Once the GMCA is delivered to JPL, it will be subjected to a suite of pre-defined performance tests emphasizing electronic and networking system performance. Once these tests are passed, the MCS, LOGSNet and GMCA will be integrated electronically, and then the integrated electronic system will be transported to the OCTL telescope for the final step of integration. Once the GMCA is delivered, its single-mode fiber input must be optically integrated with the optical output of the adaptive optical system of the IOS. Likewise, the output of the High Power Amplifier of the GMCA must be physically and optically integrated with the remainder of the transmit beams.

The remaining system to be integrated is the stand-alone equipment of the ACM system; that equipment has been put in place already at the telescope facility, in order to check out its performance and begin accumulating an advance database of atmospheric/optical conditions. Its integration consists of communications with the MCS, both commands to the ACM and receipt of data from the MCS.

IV. Expected OGS-1 Performance

During an LCRD link, a maximum information rate of 1.24 Gb/s will be broadcast using DPSK modulation, and 321 Mb/s can be broadcast under PPM (M=16). OGS-1 is to collect the downlink signal irradiance from the GEO satellite with its 1-meter aperture, and inject that signal into the single mode fiber at the input of the GMCA receiver. This requires the AO system of the IOS to compensate the received signal wavefront for the atmospherically-induced aberrations, producing a high Strehl ratio at the appropriate numerical aperture and mode area to maximize coupling of the signal to the GMCA input fiber. The AO system has been designed to operate across the conditions of the atmospheric optical channel at Table Mountain Facility, correcting across a 28x28 sub-aperture array with a wavefront sensor (WFS) that can run at an update rate in excess of 10 kHz [8].

To understand the OGS-1 performance, several wave-optics simulations were run in order to characterize:

(1) the propagation of the downlink signal and the corresponding time series at the aperture of OGS-1,

(2) the AO functioning, namely the efficiency of the signal coupling into the single mode fiber at the GMCA input, and

(3) the time series of the uplink signal at the space terminal.

The wave-optics simulations were run at two different conditions of the atmospheric optical channel at OGS-1:

(1) Nominal condition, representing the 50% of the CDF the statistics of the astronomical seeing and ground wind speed, corresponding to an atmospheric coherence length (or Fried parameter) of r_0=5.2 cm at zenith, and ground wind speed of 2.3 m/s,

(2) Worst condition, corresponding to the 90% of the CDF of the astronomical seeing, with an r_0=2.7 cm, and ground wind speed of 5.6 m/s.

The simulations assumed a modified Hufnagel-Valley turbulence model [9], a ground level of 2200 meters MSL (the altitude of OGS-1), and the profile of the wind speed at the OGS-1 site. Though there is still some uncertainty about the final location of LCRD GEO platform (which determines the ground terminal elevation angle), an elevation angle of 45 degrees was assumed.

Some of the results of the wave-optics simulations are shown in Figures 6 through 8, where, for convenience, only two seconds of the output time series are depicted. Figures 6 and 7 depict the time evolution of the downlink signal injected into the fiber and the uplink signal at the flight terminal. The downlink signal experiences limited fading due the averaging effects of the 1-meter aperture of OGS-1, with related scintillation index (σ_I^2) ranging from 0.0007 for the nominal case to 0.0013 for the worst case conditions. In contrast, the uplink signal simulation is observed to experience stronger fading with scintillation index as large as 0.29 in the worst case, which produces signal fades in excess of 30 dB (Fig. 7).

Figure 8 shows the time variation of the coupling efficiency of the AO system under nominal and worst conditions. Particularly noticeable is that, in both cases, the OGS-1 AO system is expected to provide a coupling efficiency larger than 55%, the minimum required by the project.

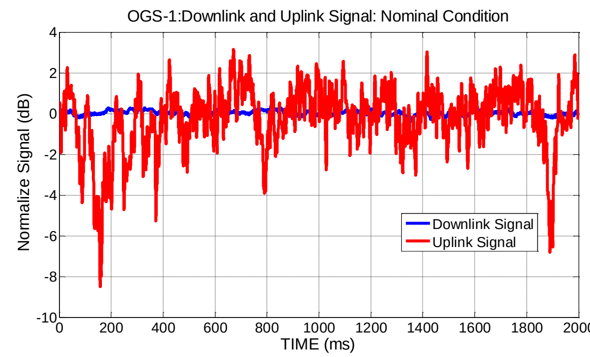

Fig. 6. OGS-1 Wave-Optics simulation results; Nominal Conditions, Downlink signal injected in a single mode fiber. Simulation inputs include Fried parameter of 5.2 cm. and ground wind speed of 2.3 m/s.

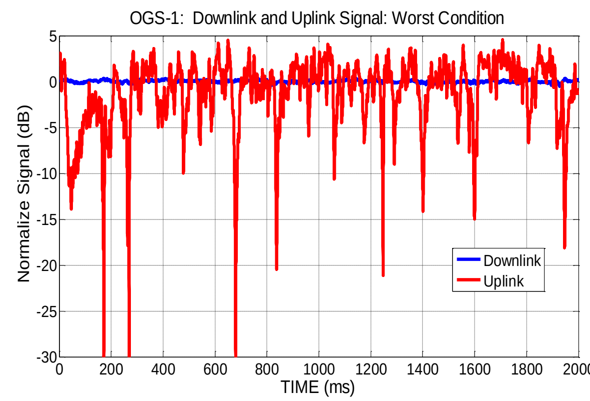

Fig. 7. OGS-1 Wave-Optics simulation results; Worst Conditions. Downlink signal injected in a single mode fiber. Simulation inputs include Fried parameter of 2.7 cm. and ground wind speed of 5.6 m/s.

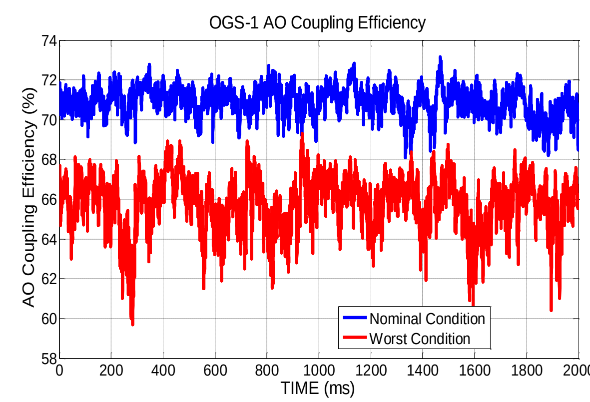

Fig. 8. OGS-1 Wave-Optics simulation results for AO coupling efficiency. Mean values: Nominal conditions 70%; Worst conditions 65%

An overall summary of the simulation results is captured in Table 1. Among the important parameters, Table 1 provides the coherence time of the uplink and downlink signals derived from their respective simulated time series. The coherence time is here defined as the 1/e-width of the autocorrelation function of the time series, and in practical terms may indicate a measure of the duration of the signal fading. [10].

TABLE I. WAVE OPTICS SIMULATION RESULTS SUMMARY

OGS-1 Wave Optics Simulation Summary		
	Nominal	**Worst**
Downlink σ_I^2	**7E-4**	**1.3E-3**
Uplink σ_I^2	**0.09**	**0.29**
AO Coupling Efficiency (%)	**70**	**65**
Downlink Coherence Time (ms)	**29**	**26**
Uplink Coherence Time (ms)	**16**	**10**

In addition to enabling relay links between two different ground stations, LCRD also enables close loop links using a single station, where the uplink signal is routed by the space terminal and broadcast back to the transmitting station. This particular 'loop-back' link is particularly useful for validating the performance of a singular ground station. To that end, we will evaluate the expected performance of OGS-1 loop-back links for DPSK and PPM modulation.

The LCRD relay system acts as a 'bent pipe', essentially functioning to demodulate and retransmit the uplink signal to downlink (no decoding/coding). A better way to describe the link performance is to use an uplink/downlink margin curve. In this way, instead of having a fixed margin level when we close the link, the link performances are described by a pair of continuous uplink and downlink values that result in a closed link; in this way, a possible loss on one path of the relay (e.g. uplink) can be compensated by an excess of margin on the other path of the link (e.g. downlink).

The first step to generating this uplink/downlink margin curve for the loop-back link is to derive the relay curve indicated by the *locus of points* of photon/bit pairs (uplink,downlink) necessary to close the link with zero margin. [10]. This is shown in Fig. 9 , which compares the relay transfer curves for PPM, and DPSK at nominal conditions for OGS-1. These curves are obtained from a simulation that takes into account:

(1) uplink and downlink signal fading (as shown in Fig. 6)

(2) LCRD coding, DVB-S2 with code rate 0.5,

(3) limiting code word error rate (CWER) of 10^{-4},

(4) the 0.87 s depth of the channel interleaver used to ameliorate the fading effects, and

(5) expected receiver performance [10].

The vertical and horizontal asymptotes correspond to the required number of photons per bit to close the link at the receiver when the downlink and the uplink are error-free. The difference between the vertical and horizontal asymptotes are mainly due to the larger fading that the uplink beam experiences. Finally, DPSK is a more efficient modulation than PPM, which is reflected by the fact that more photons are required per bit to close the link with zero dB margin.

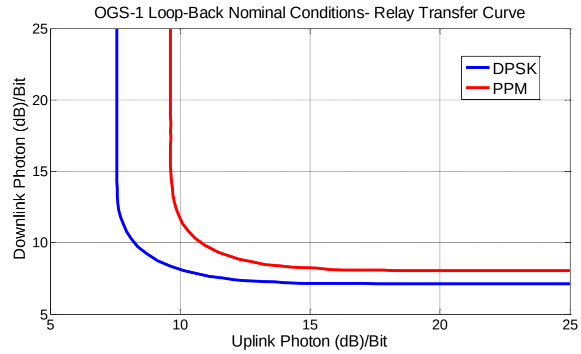

Fig. 9. OGS-1 Loop-Back relay transfer curves for PPM and DPSK modulation.

The overall margin curves are derived by calculating the distance of the relay transfer curve from the planned operational link points, the number of photons/bit available at the receiver (uplink and/or downlink) after anticipated losses in the link budget. The OGS-1 transmitter is capable of an average power of 10 W, while the space terminal transmits only 0.5 W average power. Starting from these two values, the link budget values are used to derive the residual photons/bit at the receiver. Note that the DPSK modulation option is designed for a maximum data rate of 1.24 GBPS, while the PPM maximum data rate will be 321Mb/s, which results in more photons/bit available for the PPM modulation relative to DPSK.

The DPSK and PPM margin curves for OGS-1 loop-back link at nominal conditions are shown in Fig. 10. As expected, the PPM modulation produces a larger margin at lower data rates and a larger number of residual photons/bit available at the receiver(s). However, for the DPSK modulation we can expect a margin of up to (7dB, 9dB) at the knee, indicating that OGS-1 should successfully close the loop-back link at 1.24 Gb/s.

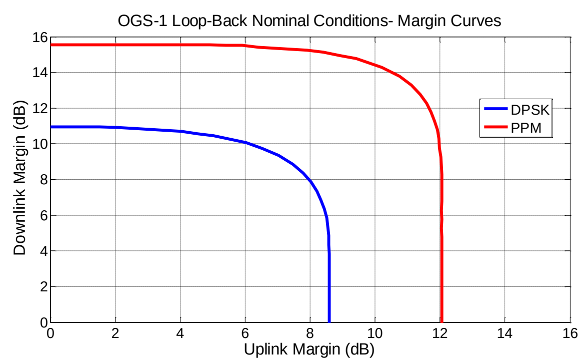

Fig. 10. OGS-1 Loop-Back Margin curves for PPM and DPSK modulation.

A number of factors affecting the link will be explored throughout the anticipated 5-year duration of the LCRD experiment. Worse seeing conditions result in margin curves (not shown here) with lower margin. Clouds can impact the link by introducing a static transmission loss, so links will be characterized over different cloud cover conditions. Uplink pointing errors can manifest as a pointing loss and excess fading that can reduce the link capacity and deviate from the expected data transfer curves. However, by operating in burst mode at a lower data rate, the system should be able to overcome many of these challenges.

We expect that, with experience operating such links under variable atmospheric conditions, we can obtain data on the optimum operating points to for the given conditions. Such experience will be of great value in siting, designing and

V. SUMMARY

OGS-1 is a critical part of the LCRD project in ushering in a new high-bandwidth capability in NASA's suite of communications tools. It is being built with a state-of-the-art AO system for efficiently coupling the collected wavefront into the single mode fiber input to the ground modem. In addition, OGS-1 has a well-appointed weather station and atmospheric channel monitoring system on site for detailed correlation with link performance. A highly capable networking system is also under development to demonstrate simultaneous operation of up to 12 virtual channels, either real or simulated data, from among four different service types.

The OGS-1 development project is in the final phase of subsystem development, and is preparing for integration and test of the system in late 2017 and early 2018. Optical integration will proceed at the OCTL telescope while electronic and networking integration will run along a parallel track at JPL. These two tracks will be brought together at the telescope during final integration in the latter half of 2018.

We have begun analysis of link curves under a wide set of conditions, and are confident that sufficient margin exists to perform robust DPSK and PPM links in loopback mode.

We expect the OGS-1 ground station to be fully tested and ready to support the LCRD project when the space platform launches in 2019. With its high-throughput and uniquely adaptable networking system, OGS-1 will probe the capabilities of high bandwidth ground-to-GEO communications over a variety of service types and operational scenarios. Researchers will be aided in understanding the best operating points for various service and link types over a wide range of atmospheric conditions. Armed with the tools provided by OGS-1 and LCRD in general, optical communications researchers will obtain a wealth of information for designing and optimizing the next generation of high-bandwidth space-to-ground communication systems.

ACKNOWLEDGMENT

The authors gratefully acknowledge the work performed by the entire LOGS team in developing the technology to support this demonstration, and the many fruitful discussions and conversations.

REFERENCES

[1] B. L. Edwards, D. J. Israel, K. E. Wilson, J. Moores, A. Fletcher, “Overview of the Laser Communications Relay Demonstration Project”, Space Operations Conference, June 2012.

[2] B. L. Edwards, D. J. Israel, “A Geosynchronous Orbit Optical Communications Relay Architecture”, IEEE Aerospace Conf., March 2014.

[3] D. M. Boroson, “Overview of the Lunar Laser Communication Demonstration”, Proc. Int. Conf. on Space Optical Sys. and Applic. (ICSOS), 2014, Kobe, Japan, May 2014.

[4] D. M. Boroson and B. S. Robinson, “The Lunar Laser Communication Demonstration: NASA's First Step Toward Very High Data Rate Support of Science and Exploration Missions”, Space Sci. Rev., vol. 185, pp. 115-128, December 2014.

[5] A. Biswas, J. M. Kovalik, M. W. Wright, W. T. Roberts, M. K. Cheng, K. J. Quirk, M. Srinivasan, M. D. Shaw, K. M. Birnbaum, “LLCD operations using the Optical Communications Telescope Laboratory (OCTL),” Proc. of SPIE, 8971, 89710X-1-16, 2014.

[6] W. T. Roberts, D. Antsos, A. Croonquist, S. Piazzolla, L.C. Roberts, V. Garkanian, T Trinh, M. W. Wright, R. Rogalin, J. Wu, and L. Clare, “Overview of Ground Station 1 of the NASA Space Communications and Navigation Program”, Proc. SPIE, vol. 9739, February, 2016.

[7] K. E. Wilson, J Wu, N. Page, M. Srinivasan, “The JPL Optical Communications Telescope Laboratory (OCTL), Test Bed for the Future Optical Deep Space Network”, JPL, Telecommunications and Data Qcquisition Progress Report 142-153, February 2003.

[8] L. C. Roberts Jr., R. Burrus, J. E. Roberts, S. Piazzolla, S. Dew, T. Truong, S. Fregoso, N. Page, “Performance Predictions for the Adaptive Optics System at LCRD's Ground Station 1”, Proceedings of Imaging and Applied Optics, OSA, 2015.

[9] G. C. Valley, “Isoplanatic Degradation of Tilt Correction and Short – Term Imaging Systems,” Appl. Opt. 19, 574-577, 1980.

[10] B. Moision, S. Piazzolla, J. Hamkins,' Fading losses on the LCRD free-space optical link due to channel turbulence,' Proceedings Volume 8610, Free-Space Laser Communication and Atmospheric Propagation XXV (2013), SPIE, San Francisco, CA